



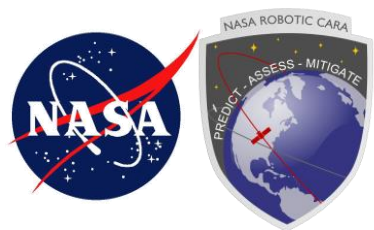
CARA Status and Upcoming Enhancements

a.i.Solutions/Megan Johnson

NASA CARA Team

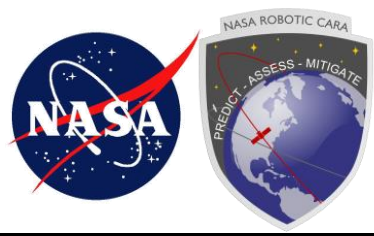
Spring 2016 A-Train Mission Operations Working Group (MOWG)

13 APR 2016

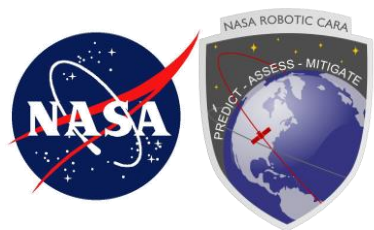


Agenda

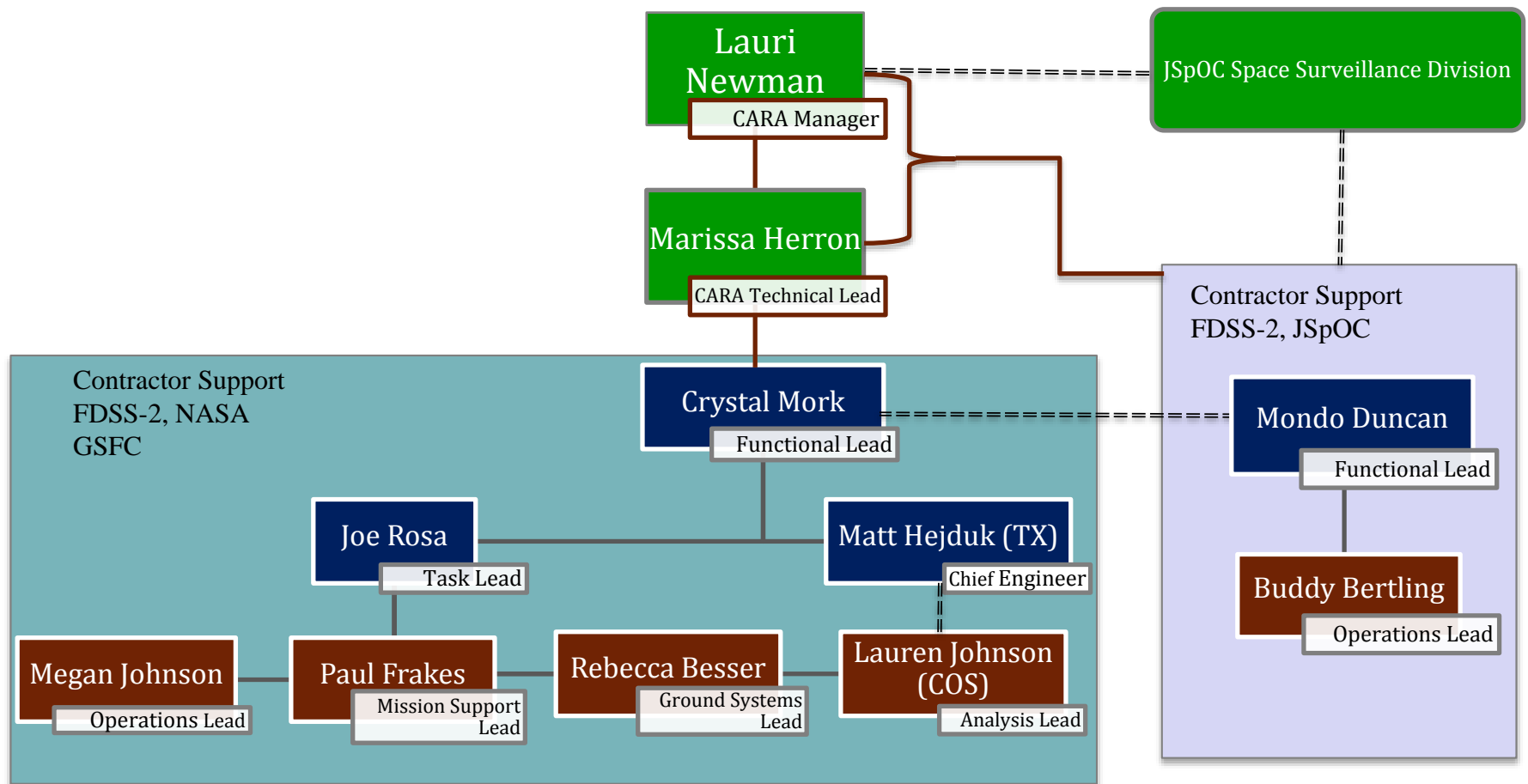
- **CARA Operational Highlights**
 - Organization Chart
- **CARA Service Enhancements Recap**
 - CAS 8.2 Release Content
 - Maneuver Trade Space (MTS) 2.1
 - Sensor Coverage 1.0
 - CAS 8.3 Release Content
- **Special Topics**
 - CARA OSA Enhancements
 - Ephemeris Naming Convention
 - Maneuver Screening Processing
 - FSO Communication Update
- **CARA S-Band Fence Preparation Activities**
 - S-Band Fence (SF) description
 - SF issues for CA
 - CARA actions: programmatic
 - CARA actions: problem definition and scoping studies
 - CARA actions: new CA paradigms
- **CARA Statistics**
- **Questions and Discussion**

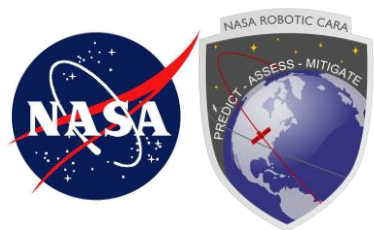


CARA OPERATIONAL HIGHLIGHTS



CARA Organization - Personnel





CARA Operational Highlights

- **LEO Launch Support**

- Jason-3: 1/17/16
 - In early orbit/check-out
 - no conjunctions identified since launch
- ASTRO-H: 2/12/16

- **GEO/GTO launch support for commercial spacecraft**

- INMARSAT-F3: 8/28/15
- MEXSAT-G2: 10/2/15
- IntelSat-29: 1/27/16
- SES-9: 2/24/16

- **Flyby Support**

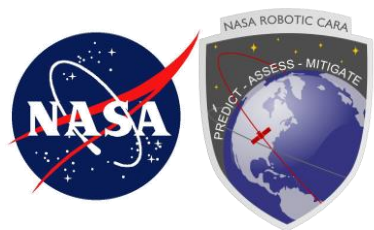
- Hayabusa-2: 11/24/15

- **SAC-D emergency operations support**

- **Held first CARA Open House SEP 2015**

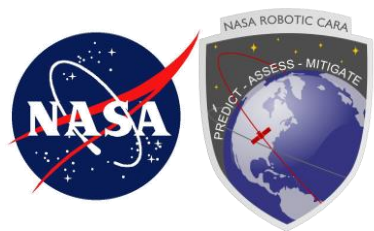
- **Certified 2 new CARA analysts DEC 2015**

| Mission | HBR (m) |
|-----------|---------|
| Aqua | 20 |
| Aura | 20 |
| CALIPSO | 15.7 |
| CloudSat | 3.5 |
| GCOM-W1 | 20 |
| Landsat 7 | 20 |
| Landsat 8 | 9 |
| OCO-2 | 6 |
| Terra | 20 |

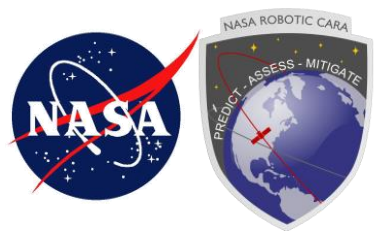


Importance of CA Users Forums

- **Users Forums:** 5 Users Forums in past 12 months!
 - February 2015: Upcoming Software Release Enhancements
 - March 2015: Maneuver Trade Space 2.0
 - April 2015: Owner/Operator Predicted Covariance Recommendations
 - October 2015: CAS 8.2 Software Release & Sensor Coverage
 - March 2016: CAS 8.3 Software Release & CARA OSA improvements
 - **NASA Robotic CARA Team hosts Users Forums to:**
 - Communicate upcoming changes in CA process
 - Share ideas and weigh-in on CA issues
 - Present analysis results
 - Debrief high interest events & discuss lessons learned
 - Address CA 'Hot Topics'
 - Conduct open forum with CA users: present & future
 - Solicit comments/ideas/input from user community
 - develop better plans and processes to meet requirements with desired outcomes
- *Mission feedback is very important to help develop future requirements, evaluate enhancements, and address concerns**

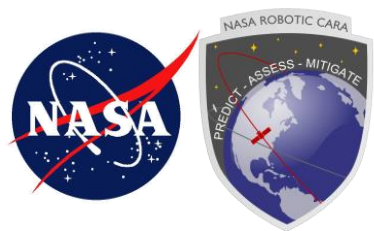


CARA SERVICE ENHANCEMENTS



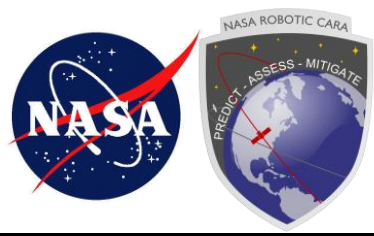
CAS 8.2: Recap

- **Promoted to Operations on 10 NOV 2015**
 - No interruptions to report delivery or other CIRA services
- **Release designed to focus on report and email updates:**
 - Report generation speed increase
 - Addition of risk flags
 - Bug fixes identified from the last release (CAS 8.1)
 - Summary Report updates and enhancements
 - Red alert email updates
 - Text messaging availability
 - Notification of red and yellow event receiving updates in addition to totals

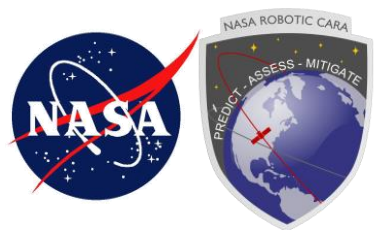


CAS 8.2: Summary Report Items

- **Satellite-specific mission risk thresholds**
- **Pc in Vegas odds**
- **More distinctive bolding**
- **New Event flags**
 - New Track Since Last Estimate
 - Above Mission Planning Threshold
 - Repeating Conjunction
 - Post-maneuver/short arc solution
- **Additional time history plot annotations**
 - Tracking since last OCM indications on plot
- **Additional plots**
 - O/O Miss + 1-Sigma time history bar plot
 - ASW & O/O Conjunction Plane plots
- **Ephemeris end date**
- **Appendix definition updates**
- **Hyperlinks between Summary and Details sections**

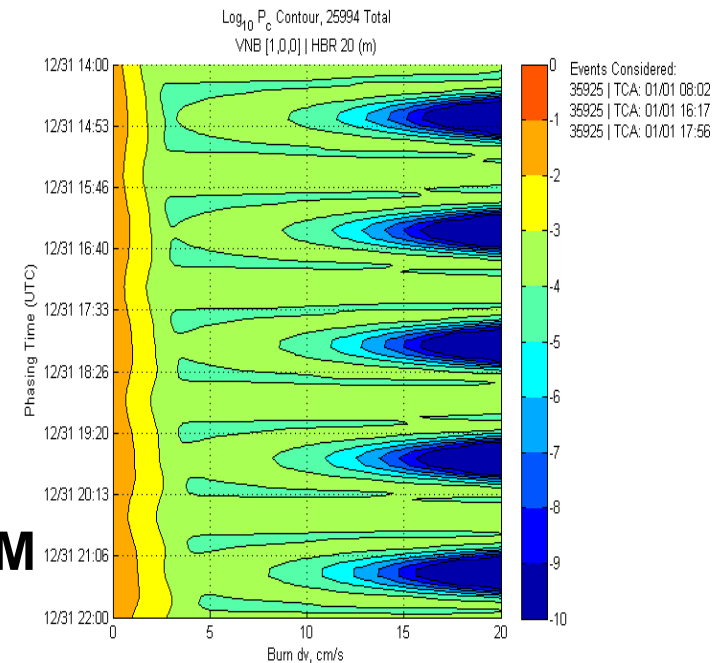


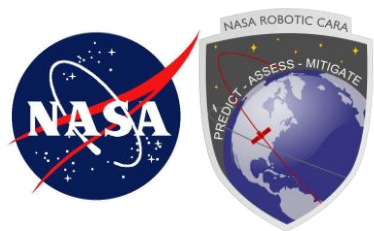
MANEUVER TRADE SPACE (MTS) 2.1



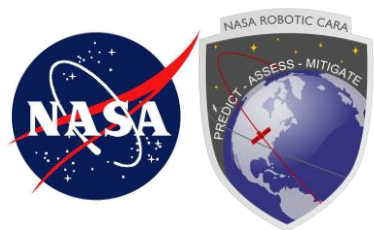
MTS 2.1: Recap

- Promoted to operations 26 JUN 2015
- Additional Total P_c plot including a summary of all conjunctions included in the run
- Multiple input sources for chemical burn cases
 - Runs on combinations of state & covariance sources
 - OCMs, VCMs, ephemerides, and synthesized covariance
- Differential drag situations addressed
 - Input of O/O vs ASW OCMs with an input O/O ephemeris
- Increased optimization of run times for OCM vs. OCM cases to speed up runs
- Updated GUI to support additional options
- Automated daily update of the solar flux file



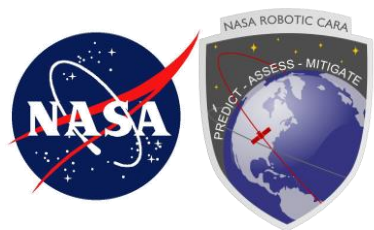


SENSOR COVERAGE 1.0



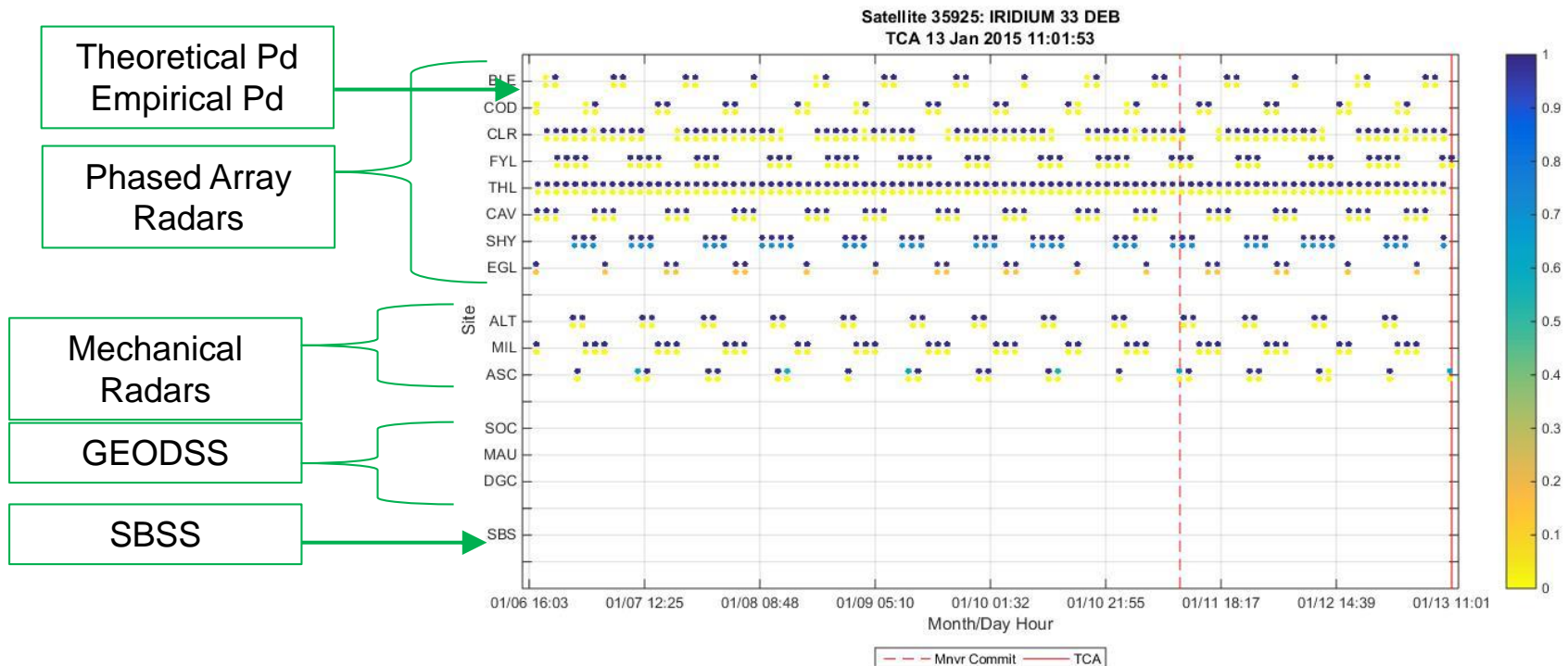
Sensor Coverage Tool: Recap

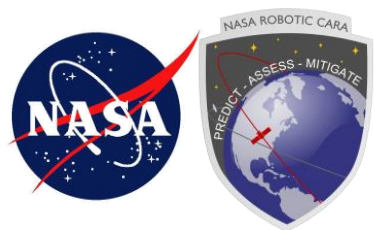
- **Provides/evaluates predicted satellite SSN tracking opportunities**
 - Tabular and graphical display of pass opportunities
- **Features**
 - Calculates look angles between satellite and SSN sensors using AFSPC Astro Standards software
 - Calculates theoretical signal-to-noise ratio (SNR) and probability of detection (Pd) using JSpOC sensor models
 - Calculates “empirical” Pd for particular satellite-sensor pair using historical database of sensor tasking response
 - Ratio of # of successful acquisitions to # of times tasked, over last 25 taskings
 - Determines the likelihood of sustaining/improving the quality of OD



Sensor Coverage Tool: “Backup” Full Information Display

- **Full results graph (backup chart in HIE briefing package)**
 - Shows all sites, all passes
 - Theoretical Pd is above, Empirical Pd below for each pass
 - Color bar at right gives values based on Pd percentage



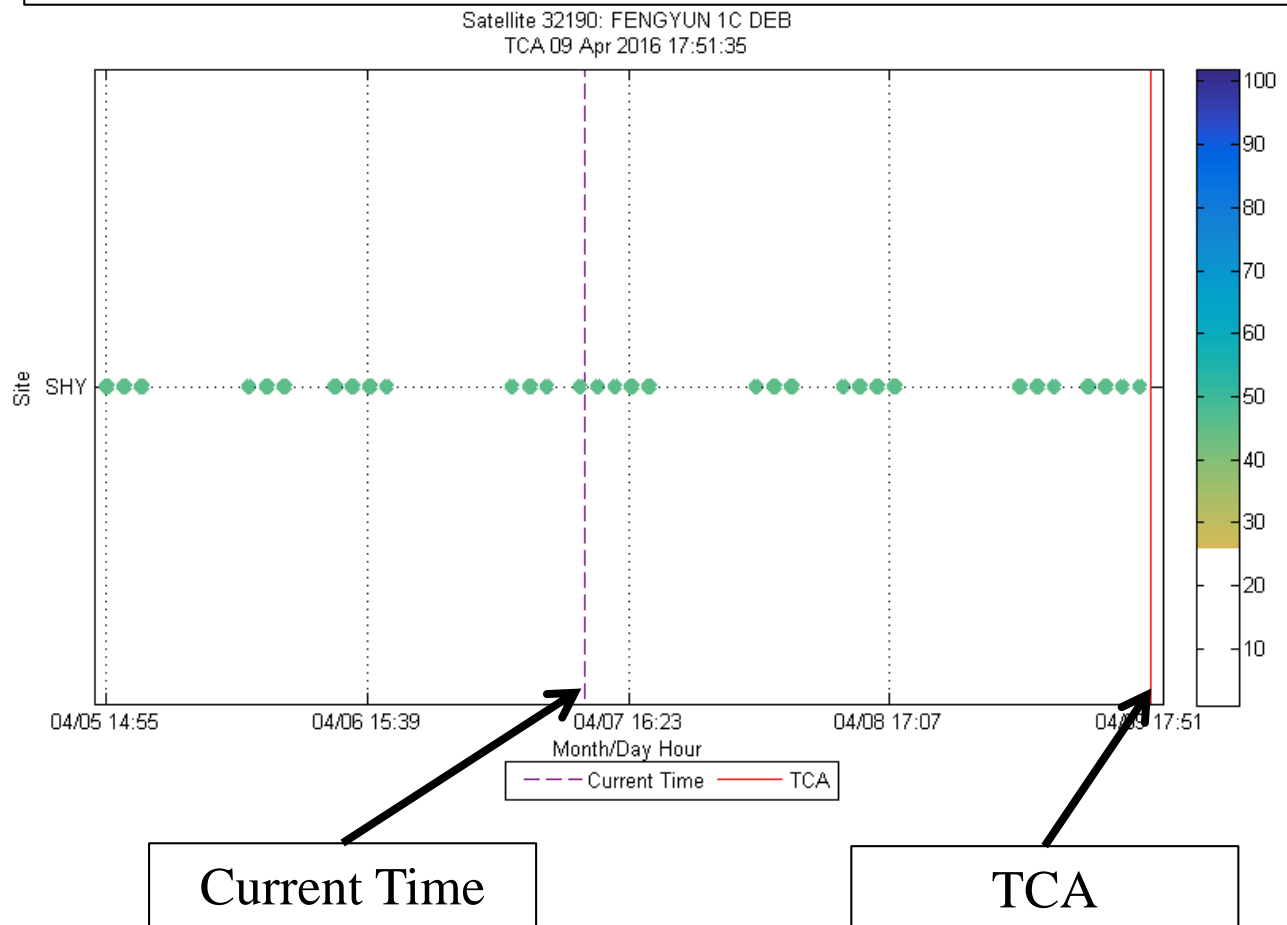


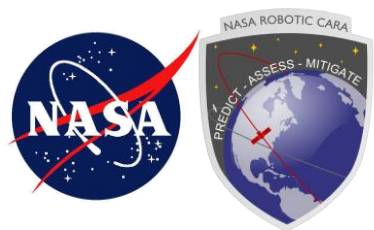
Sensor Coverage Tool: Consolidated Expected Tracking Display

- **Summary Graph:**

- Only empirical Pd values
- Data displayed only where empirical Pd > 25% (can be manually changed)
 - Only sites with predicted passes shown
- Color bar provides percentage to color mapping
- Included in HIE briefing

Full “Back up” information display too busy to give focused assessment of expected tracking situation





Sensor Coverage Tool: CONOPS

How the tool is useful:

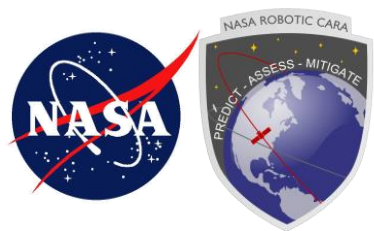
- Sensor Coverage data provides predictive insight into when the conjunction data has the potential to change

When tool will be used:

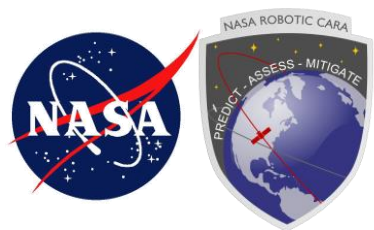
- At analyst discretion for non-HIE events
- At mission request for HIE events without briefings
- When providing an HIE briefing

What will be provided:

- Summary graph with only tracking opportunities above a settable empirical P_d
 - Used as main presentation/discussion item
- Full results graph
 - To be included as HIE briefing backup slide
- Disclaimer for caveats

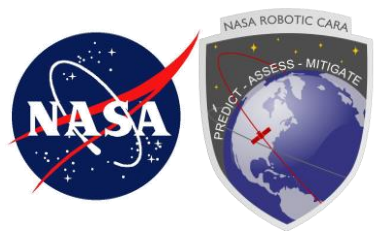


CURRENT AND UPCOMING SOFTWARE RELEASES



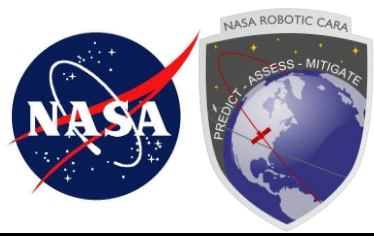
CAS 8.3: Recap

- **As presented at the 1 MAR 2016 User's Forum, new features to improve performance and provide additional updates for HIEs**
- **Data freshness**
 - Reduced screening and data generation times
 - Reduced CARA report delivery processing time
- **Enhancements**
 - Upgraded interface between CARA and JSpOC
 - Deliveries from the JSpOC will include a single compressed data file rather than OCMs and supporting files
 - Removed ephemeris limit for maneuver screenings; to allow 5 maneuver ephemeris screening options for HIEs
 - Support for HIE off-cycle 1v1 deliveries
 - Generates and delivers individual summary reports
 - Included software updates to support various message format deliveries (OCMs, CDMs, and JMS considerations)
- **Delivery April 2016**

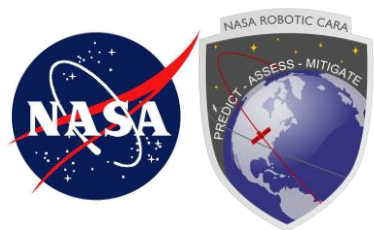


CAS 8.4 and Beyond

- **Continued performance enhancements**
 - Report generation/delivery
 - Automated processing speed
- **System, software and hardware refresh**
 - Improved architecture and design
 - Database redesign in preparation for Space Fence and JMS
 - Researching alternatives for CARS system expansion including cloud-based solutions and local virtual environment



SPECIAL TOPICS

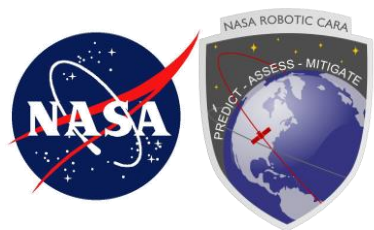


CARA OSA Enhancements

- **Designed to enhance CAS 8.3 implementation, standardize CA functions (JSpOC), and provide performance improvements**
- **3 full SP catalog LEO screenings per day**
 - 2 full catalog HEO/GEO screenings per day
 - Removal of O/O ephemeris delivery restriction
 - 3 opportunities per day for inclusion in full catalog screening

| SP Catalog Screening | Ephem Delivery Deadlines (ET) | Estimated Report Delivery Time (ET) |
|----------------------|-------------------------------|-------------------------------------|
| Full Screening #1 | 9 am | ~1 pm |
| Full Screening #2 | 5 pm | ~9 pm |
| Full Screening #3 | 1 am | ~5 am |

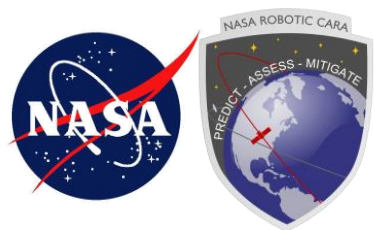
- **Increased OSA operational hours**
 - Now covering 20 hours per day, 7 days a week
- **Enhanced 1v1 processing**
 - Automated notification of secondary object observation receipt for HIEs
 - Automated 1v1 processing upon receipt
 - Generation of single report with CAS 8.3 promotion



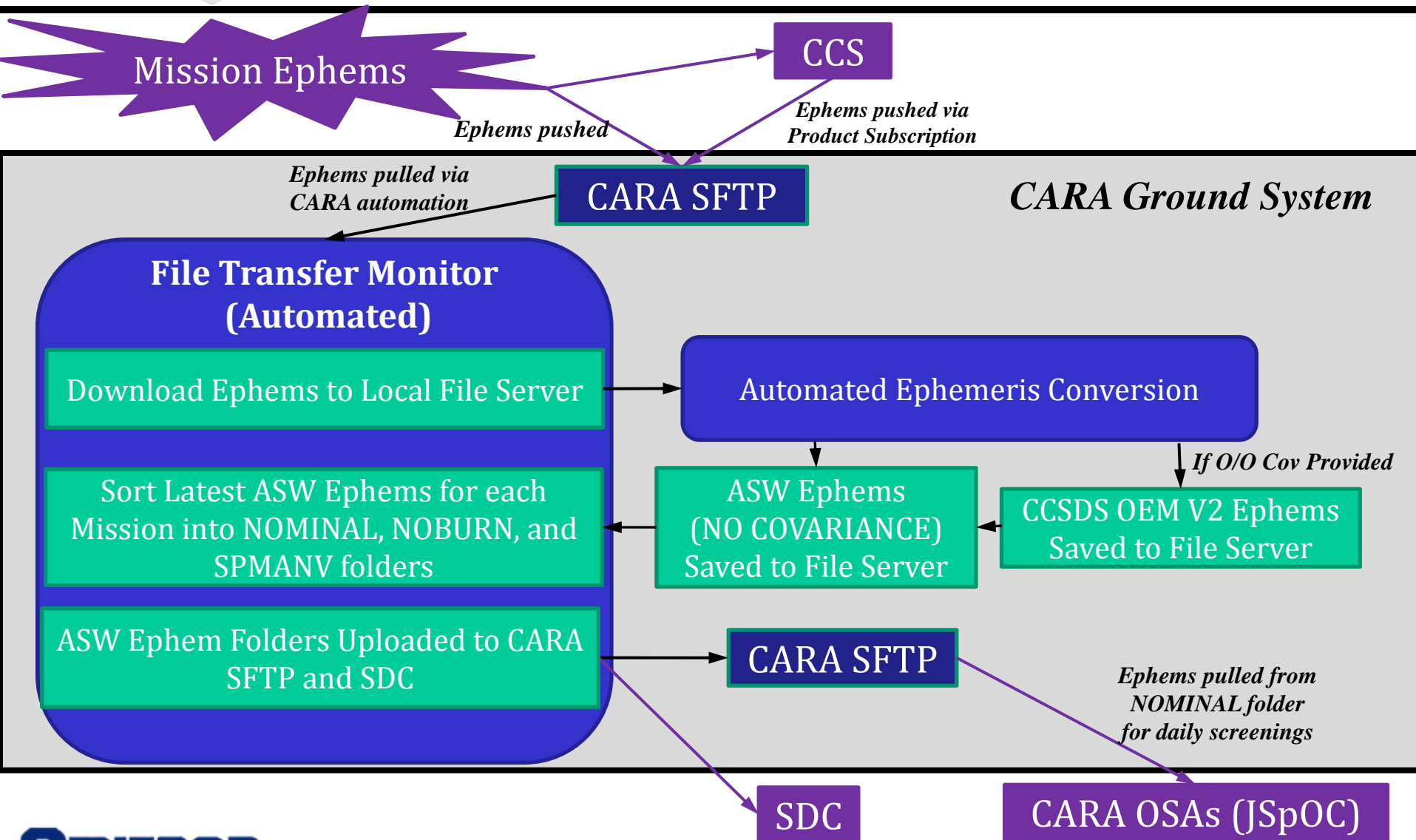
Ephemeris Naming Convention

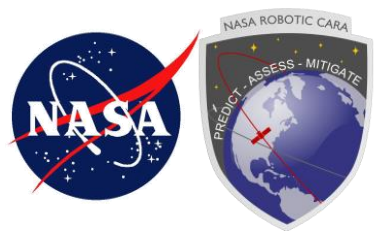
- **CARA currently processes a maximum of 1 O/O ephemeris per mission per nominal report delivery**
- **Sometimes missions deliver multiple ephemerides**
 - Burn and no-burn case
 - Multiple RMM options
- **To improve clarity, we directed a specific “key word” naming convention to be used for ephemeris deliveries:**
 - “**_NOMINAL**” – contains the nominal plan (i.e. trajectory you intend to follow), whether that includes burns or not
 - “**_NOBURN**” – contains no burns (not necessary to deliver if _NOMINAL contains no burns)
 - “**_SPMANV**” – any ephemeris that contains burns but is not the _NOMINAL (used primarily for multiple burn options)
- **OCO-2, CALIPSO, and Cloudsat have adopted this convention**
- **Aqua and Aura are testing ephemerides with the new format**

IMPACT: Using the prescribed naming convention will mitigate the risk of having the wrong ephemeris screened



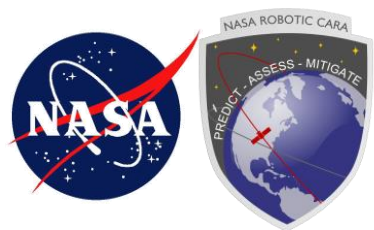
CARA Ephemeris Delivery/Ingestion Process



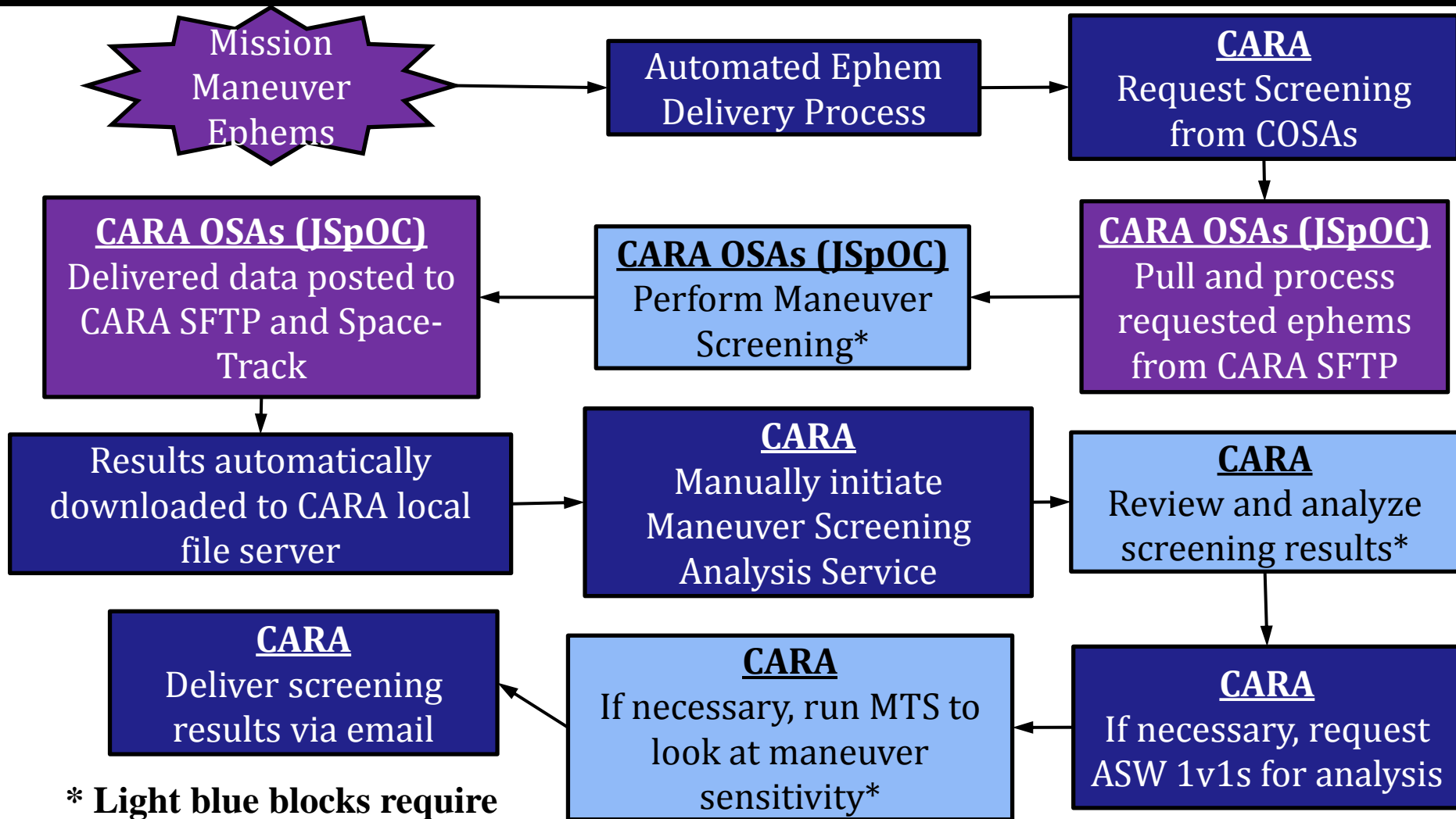


Enhanced Maneuver Screening Process

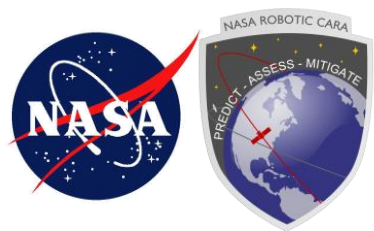
- **ESMO requested modification to existing Maneuver Screening Process to allow for multiple maneuver ephemerides to be screened simultaneously for HIEs**
 - This allows multiple burn options to be explored in a semi-automated manner
- **As of CAS 8.3, software-based ephemeris limits will no longer exist in the maneuver screening process**
 - Remain constrained by time and available resources
 - Process designed for additional maneuver screenings (**5 ephemerides per day, per mission**) to be performed upon request for HIEs that meet the following requirements:
 - Event meets or exceeds HIE thresholds
 - Within 3 days of TCA
- **Maneuver screening analysis will still remain a manual process performed by the CARA analysts**
 - All maneuver screening conjunctions will be reviewed by an analyst
 - Program/application is built specifically for analyst interactions and risk analysis



Maneuver Screening Process



* Light blue blocks require significant processing time

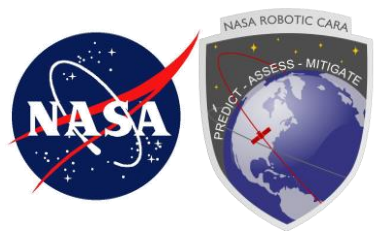


Update on FSO Communication since last MOWG

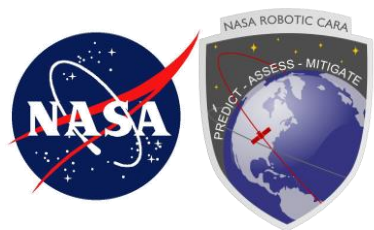
- **White paper sent to DoD to ask permission for JSpOC to send emails to Beijing Institute of Tracking and Telecommunications Technology (BiTTT) email address on NASA's behalf**
 - Request denied based on policy decisions
- **Terra event in January 2016 yielded positive results using existing method of working through State Dept**
 - Received confirmation from BiTTT that email was received
- **NASA HQ Office of International and Interagency Relations (OIIR) to work with State Department to try to formalize agreement to continue existing method**
 - OIIR revised communication template example:

The US Government has identified a close approach between the US Government satellite Terra, (satellite catalog number 25994) and the satellite SJ-11-01, (satellite catalog number 36088). The Time of Closest Approach (TCA) is 2016 Jan 16 21:37:09 UTC. The miss distance prediction as of 2016 Jan 15 04:37:35 UTC is 356.0 meters and the US Government team is computing a Collision Probability of 0.

We believe this close approach poses a low collision risk if neither satellite maneuvers. Please do not maneuver your satellite between now and TCA. Terra is not planning a maneuver between now and the TCA.

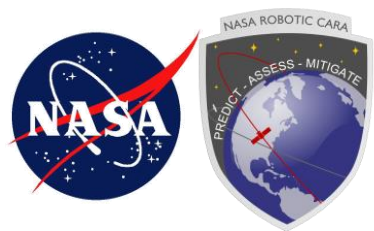


CARA S-BAND FENCE PREPARATION ACTIVITIES

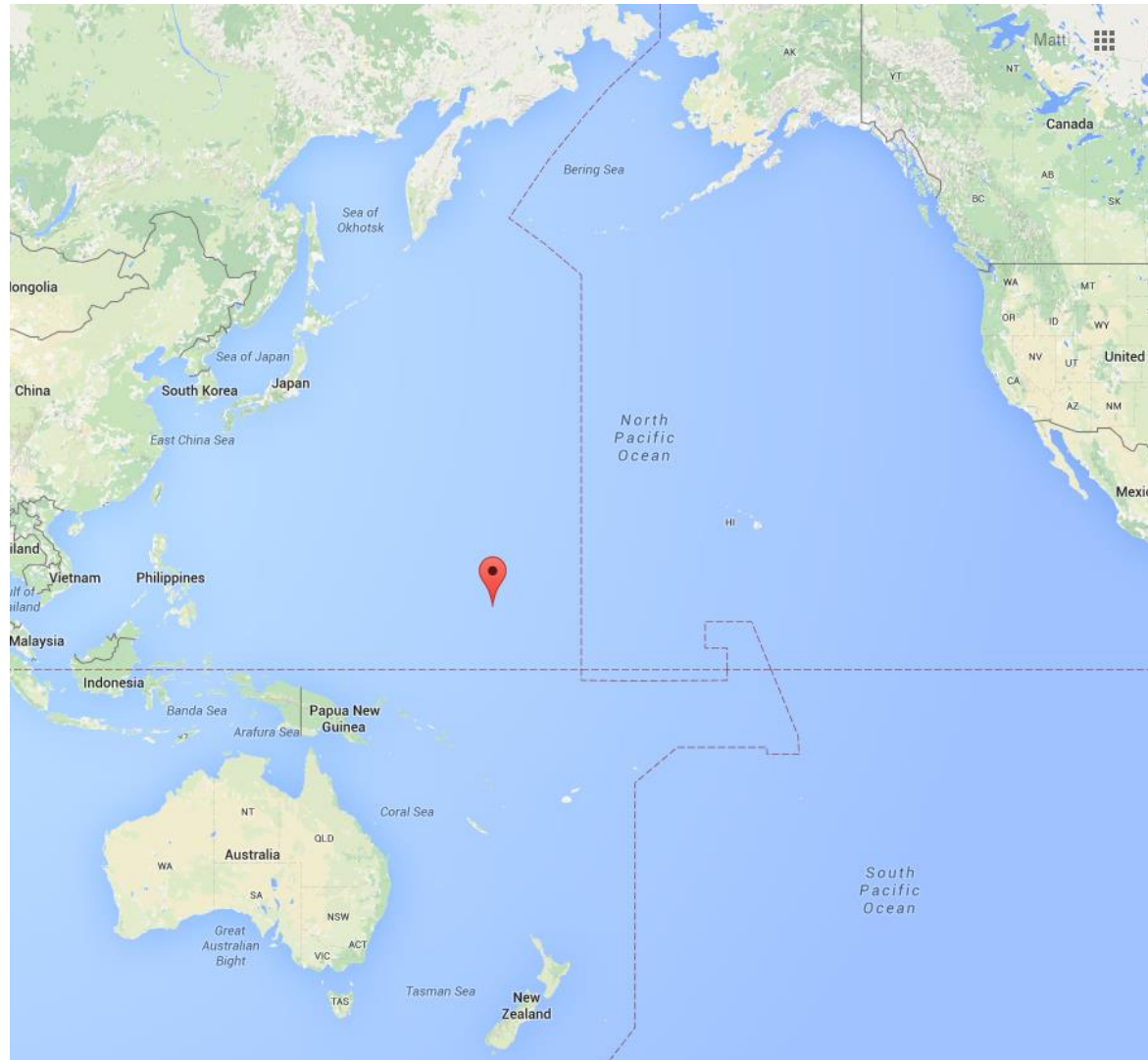


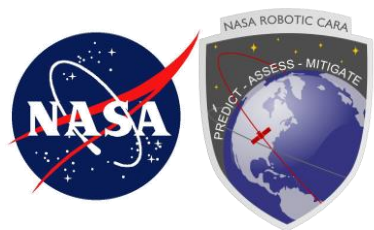
S-Band Fence: Description

- **Large-aperture S-band radar for small object tracking in LEO**
- **Near-equatorial placement at Kwajalein Atoll, Marshall Islands**
 - Option for second site, likely in Australia
- **Intended for surveillance fence operations**
 - Beams are electronically steerable to allow for extended tracking
 - Essentially a phased-array radar with “face” pointed up
 - Extended-range mode allows tracking of DS objects
- **Detectable object size in LEO better than 10 cm**
- **Two-polarization processing (PP and OP) allows high-precision RCS determination**
- **Initial Operational Capability (IOC) planned for latter part of 2018**



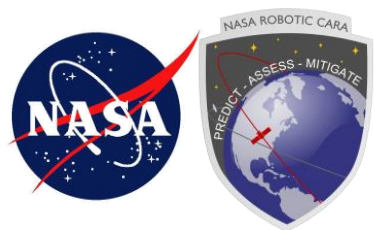
S-Band Fence: Location





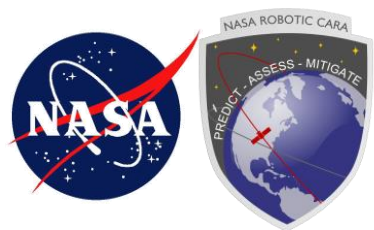
S-Band Fence: Issues for CA

- **New debris objects discovered (and maintained) only by SF**
 - Quantity of such objects (estimates range from 50K to ~150K)
 - Quality of maintenance ODs, which is governed by
 - Tracking rates
 - OD errors (expected observation errors, vector errors, and covariance sizes)
 - Maintenance strategy for objects at edge of SF detection
 - All of the above trace to issues of data actionability for CA
- **Existing debris tracked by SF**
 - OD improvements for current debris objects tracked by Shemya only
 - Effects on OD vector error and covariance sizes
- **Potential requirement for new CA paradigms, which could include**
 - CA remediation against “grouped” events using an aggregate P_c
 - Regular burns / DMU strategy to minimize conjunction risk, without actually remediating individual events unless an extremely high P_c



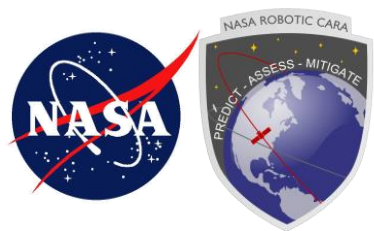
SF CARA Actions: Programmatic

- **Established strategic partnership with JSC/TOPO and Aerospace to explore, define, and respond to SF altered landscape**
 - Share data/analysis/experience and collaboratively conduct additional studies
- **Hired Dr. Doyle Hall, major figure in SSA mission area**
 - Former scientist at NASA ODPO; highly experienced with debris models, debris profiling, and the CA problem
 - Will lead CARA SF study efforts
- **Begun series of meetings with SF Program Office (Hanscom AFB) and Air Force Space Command / A5 to discuss SF issues**
 - Arrangement overseen by Tom Plumb (SES), NASA AFSPC Liaison
 - CARA asked to develop SF CONOPS options for CA and other direct tasking of sensor
- **Will submit overguide request in CARA FY 17 PPBE for S-Band-related studies and analysis**



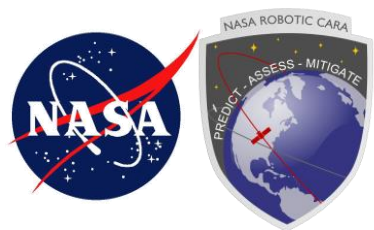
SF CARA Actions: SF Effects on CA (1 of 2)

- **Determine conjunction rate for representative payloads**
 - Obtained 2025 and 2035 S-Band debris catalogues
 - Analyze one-year period (or longer) to determine # of conjunctions per day at different screening volumes at different object sizes
 - Simulation results for current screening volume sizes can, by ratio extrapolation, give first-order idea of rates of CA events of different P_c values
 - Working in GP framework for overall characterization of large groups of conjunctions quite adequate (verified by LCOLA study)
- **Add fidelity: Estimate covariance size ranges**
 - Run OD experiments with expected tracking frequencies and SF observation error model to determine range of possible covariance sizes/orientations
 - Explicitly compute range of P_c values for each conjunction given calculated covariance possibilities
 - Summarize entire set of possible P_c values statistically to determine frequency of events at P_c values of interest



SF CARA Actions: SF Effects on CA (2 of 2)

- **Develop and propose sensor tasking CONOPS for SF**
 - Preserve fence-like operations
 - Define situations in which additional tracking prudent/indicated
 - Develop rubric and software to provide automated management of CA tasking requests



SF CARA Actions: New CA Paradigms

- **Aggregate or Total Pc**

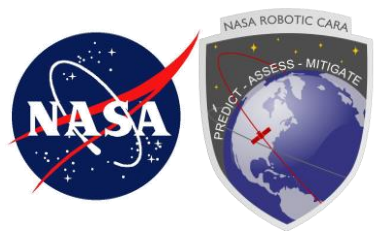
- Risk assessment and remediation based on combined effect of a (potentially large) number of conjunctions, rather than on individual discrete events
- Initial work performed on basics of calculation and use possibilities
 - Conference paper produced
- Substantial additional work required on number of CONOPS issues, especially thresholding and potential “weighting” on nearer- vs farther-term conjunctions

- **DMUs become amelioration RMMs**

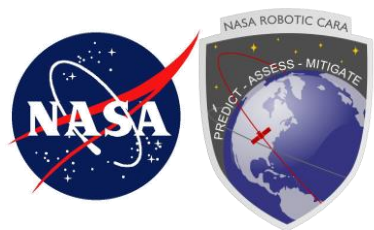
- Craft DMUs to improve longer-term conjunction posture

- **Fully stochastic, cloud-based approach**

- Would need substantial theoretical and practical development
- May not be truly viable

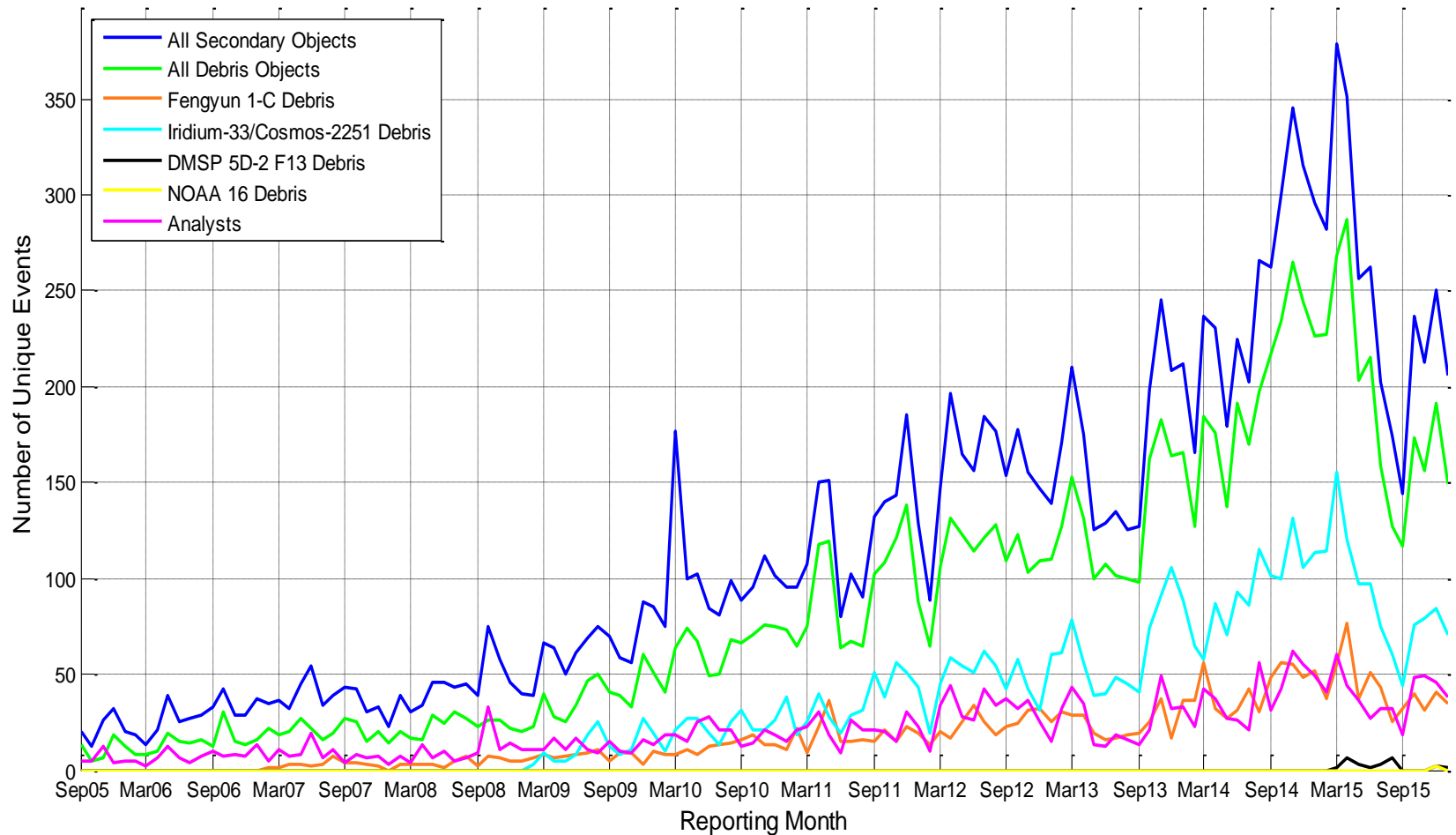


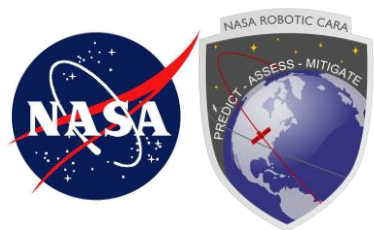
CARA STATISTICS



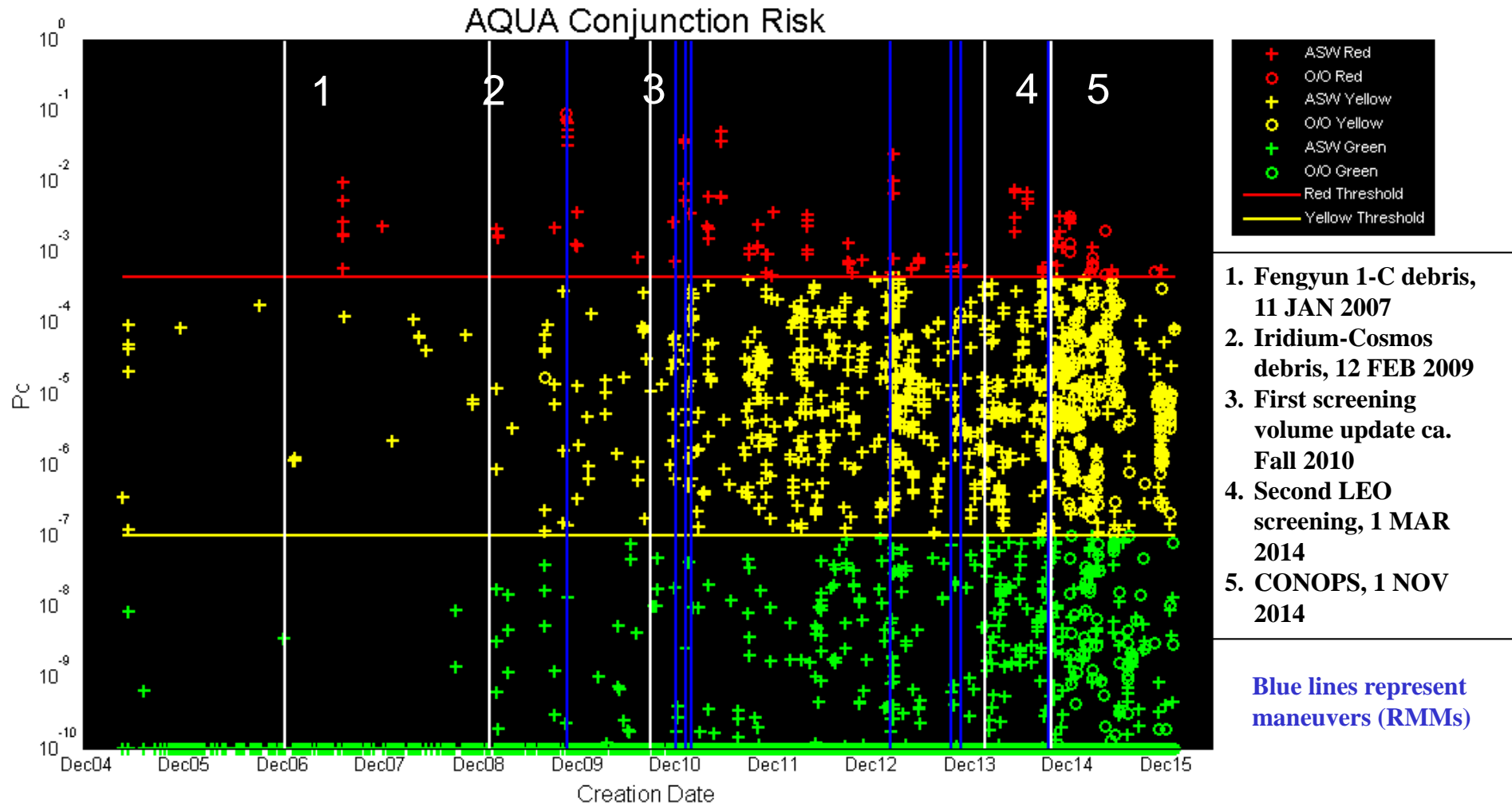
Number of Conjunctions with Current ESC Missions

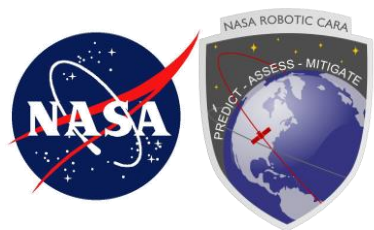
Unique Events within 0.5x5x5-km Volume by Object Type





Representative Historical Events by Risk Category



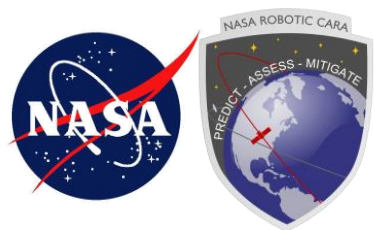


High Interest Events: 1 JUN 2015 through 1 FEB 2016

- **Tier 1: Notify O/O (email/phone call)**
 - 61 events
 - Contact may be to communicate low risk despite appearance
- **Tier 2: Brief O/O (HIE package/Maneuver Trade Space/Sensor Coverage)**
 - 31 events
- **Tier 3: Ephemeris Screening**
 - 22 events
- **Tier 4: Execute mitigation action/waive/replan maneuver**
 - 13 events (5 RMMs; 8 Re-plan/ postpone/cancel a nominal maneuver)
 - One RMM or waive/replan of nominal maneuver every ~16 days
 - Similar pace as last MOWG (Oct 2014 – Jun 2015)
- **Total Work Tier events: 127**
 - ~4 events per week, on average for ESC (down from 6 last MOWG)

Totals are for 10 of CARA's ~65 missions

- Total CARA work tiers since June 2015: **194** (of which **127** are ESC)
- Total CARA work tier 3 & 4 since June 2015: **42** (of which **35** are ESC)



Cumulative Work Tier Stats (Historical through 1 Feb 2016, All of 2015)

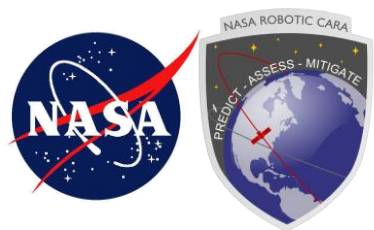
| Historical | Work Tier 1 | Work Tier 2 | Work Tier 3 | Work Tier 4 | Total |
|--------------|-------------|-------------|-------------|-------------|-------------|
| Landsat 5 | 31 | 3 | 4 | 5 | 43 |
| Landsat 7 | 59 | 17 | 8 | 15 | 99 |
| Terra | 88 | 18 | 20 | 17 | 143 |
| EO-1 | 47 | 8 | 7 | 2 | 64 |
| SAC-C | 33 | 3 | 2 | 1 | 39 |
| Aqua | 84 | 30 | 28 | 23 | 165 |
| Aura | 105 | 30 | 29 | 17 | 181 |
| Parasol | 58 | 6 | 6 | 4 | 74 |
| CloudSat | 67 | 5 | 11 | 17 | 100 |
| CALIPSO | 118 | 3 | 4 | 7 | 132 |
| SAC-D | 27 | 4 | 12 | 9 | 52 |
| GCOM-W1 | 31 | 7 | 10 | 12 | 60 |
| Landsat 8 | 82 | 5 | 6 | 8 | 101 |
| OCO-2 | 15 | 8 | 6 | 6 | 35 |
| Total | 877 | 155 | 155 | 148 | 1335 |

Work Tier Definitions

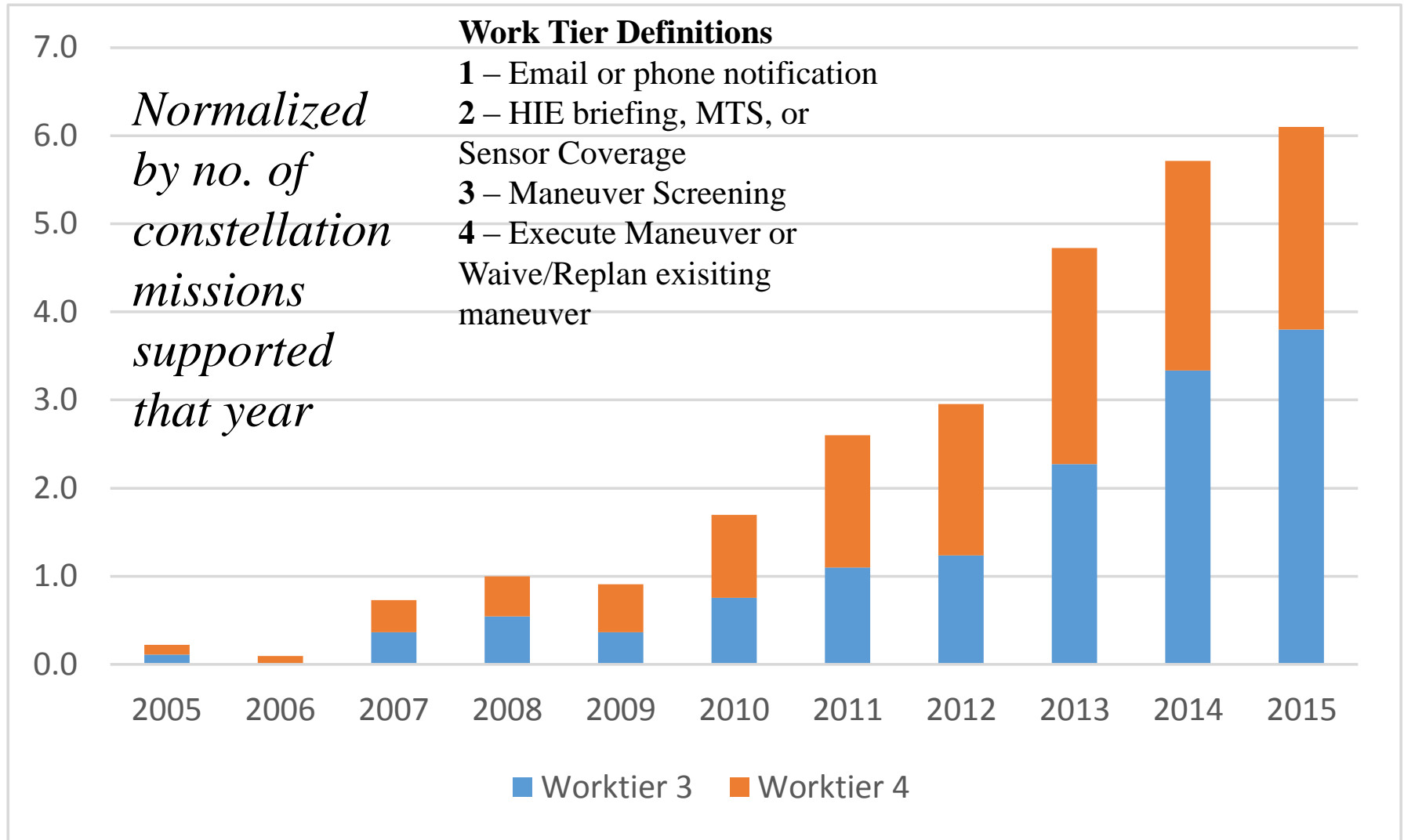
- 1** – Email or phone notification
- 2** – HIE briefing, MTS, or Sensor Coverage
- 3** – Maneuver Screening
- 4** – Execute Maneuver or Waive/Replan exisiting maneuver

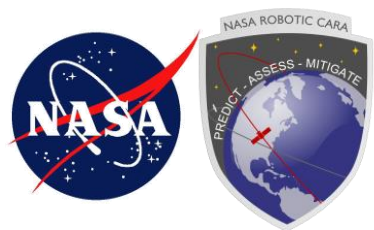
*Note that Tier 1 statistics are incomplete for Jan. 2005 – Aug. 2010. They were compiled using all past records on file and do not account for all events monitored during said time period.

| 2015 | Work Tier 1 | Work Tier 2 | Work Tier 3 | Work Tier 4 | Total |
|--------------|-------------|-------------|-------------|-------------|------------|
| Landsat 7 | 8 | 5 | 2 | 2 | 17 |
| Terra | 16 | 9 | 4 | 4 | 33 |
| EO-1 | 6 | 3 | 4 | 0 | 13 |
| Aqua | 9 | 8 | 6 | 4 | 27 |
| Aura | 14 | 9 | 4 | 4 | 31 |
| CloudSat | 8 | 2 | 3 | 2 | 15 |
| CALIPSO | 12 | 0 | 1 | 0 | 13 |
| GCOM-W1 | 12 | 3 | 6 | 2 | 23 |
| Landsat 8 | 11 | 3 | 2 | 1 | 17 |
| OCO-2 | 10 | 6 | 6 | 4 | 26 |
| Total | 106 | 48 | 38 | 23 | 215 |

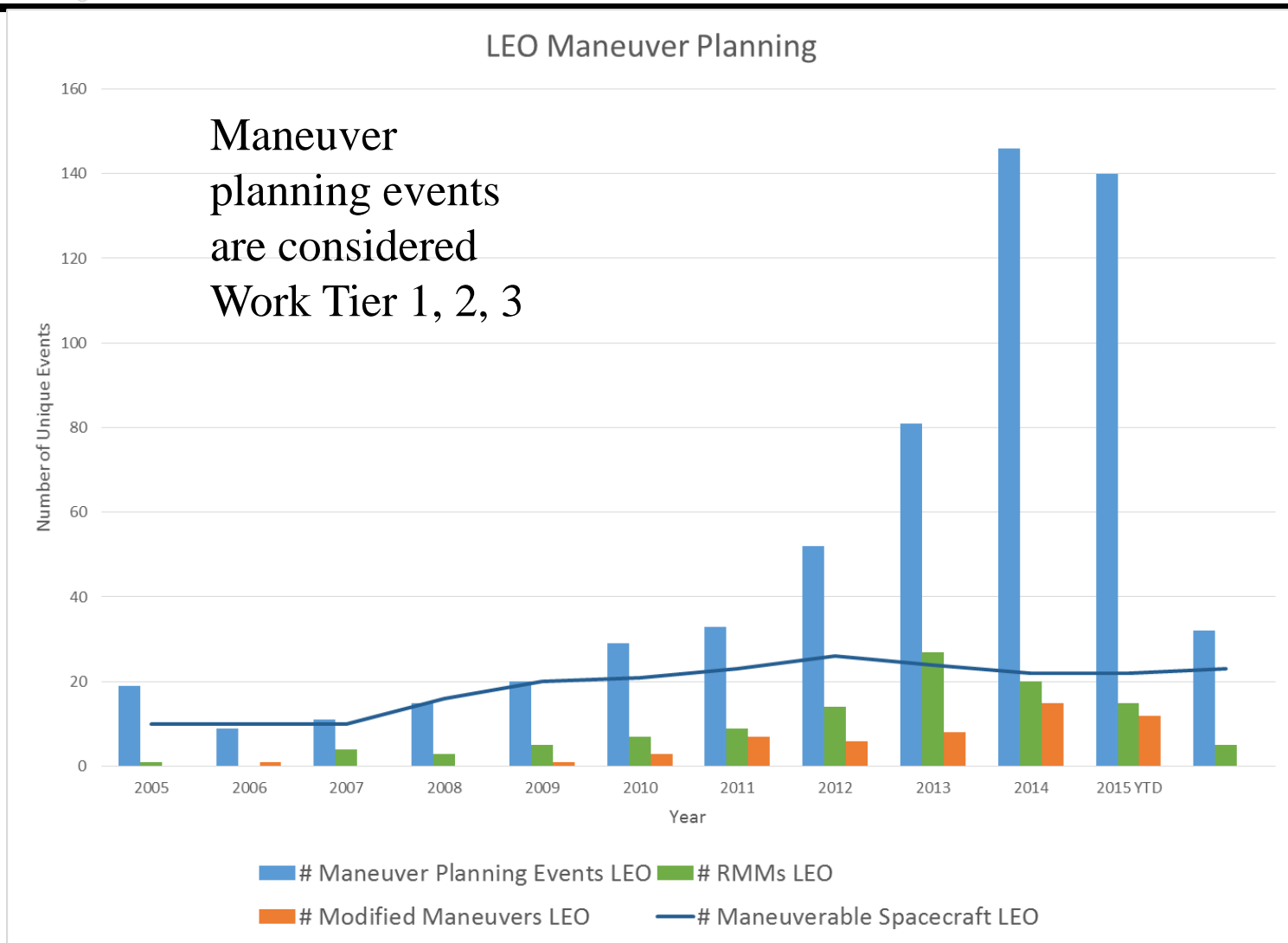


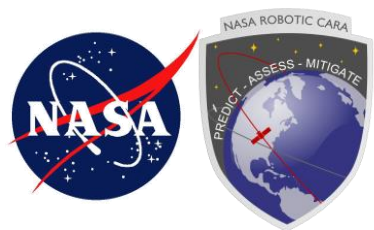
HIE History for 705-km Constellations (as of 1 Jan. 2016)





LEO Spacecraft Planning Effort Over Time

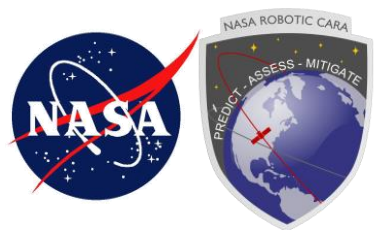




New Risk Mitigation Maneuvers (RMMs) for 705-km Constellations

| Primary Object | Secondary Object | Maneuver Date | TCA (GMT) | Min. ASW Miss Distance (m) | Max. ASW Pc | Min. O/O Miss Distance (m) | Max. O/O Pc |
|----------------|---------------------------|---------------|-------------------|----------------------------|-------------|----------------------------|-------------|
| Terra | 87692 (UNKNOWN) | 16 Jun 2015 | 16 Jun 2015 08:33 | 70 | 5.26E-2 | 147 | 2.19E-2 |
| OCO-2 | 26093 (COSMOS 2251 DEB) | 21 Nov 2015 | 22 Nov 2015 18:27 | 40 | 7.36E-4 | 137 | 6.54E-4 |
| OCO-2 | 20435 (SL-8 DEB) | 10 Dec 2015 | 10 Dec 2015 20:03 | 7 | 1.09E-1 | 13 | 8.13E-3 |
| Landsat-7 | 00478 (THOR ABLESTAR DEB) | 28 Dec 2015 | 29 Dec 2015 06:48 | 25 | 2.99E-2 | 64 | 3.03E-2 |
| Aura | 34215 (CBERS 1 DEB) | 18 Jan 2016 | 19 Jan 2016 01:17 | 143 | 1.57E-3 | 138 | 1.35E-3 |

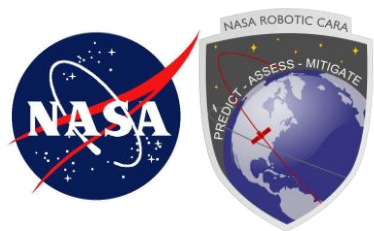
Updated as of JAN 2016



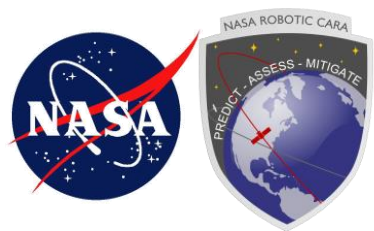
Re-planned, Postponed, Waived Off Maneuvers (705-km Constellations)

| Primary Object | Secondary Object | Maneuver Date | TCA (GMT) | Min ASW Miss Distance (m) | Max ASW Pc | Min O/O Miss Distance (m) | Max O/O Pc |
|----------------|---------------------------------|---------------|----------------------|---------------------------|------------|---------------------------|------------|
| Landsat 7 | 30844 (Fengyun 1C debris) | 25 Jun 2015 | 25 Jun 2015 02:01 | 3766 | 3.26E-05 | 310 | 2.76E-4 |
| Aqua | 21544 (Delta 1 Debris) | 15 Oct 2015 | 10 Oct 2015 20:46 | 122 | 2.27E-04 | 1439 | 1.92E-4 |
| Aura | 32344 (Fengyun 1C Debris) | 10 Nov 2015 | 06 Nov 2015 10:08 | 2056 | 4.55E-05 | 576 | 3.25E-4 |
| CloudSat | 34378 (Iridium 33 Debris) | 19 Nov 2015 | 19 Nov 2015 19:00 | 33113 | 0.00E+00 | 2009 | 2.95E-5 |
| Aqua | 00253 (Thor Ablestar Debris) | 20 Nov 2015 | 21 Nov 2015 11:13 | N/A | N/A | 647 | 8.71E-4 |
| Aqua | 22475 (SL-16 Debris) | 16 Dec 2015 | 16 Dec 2015 16:16 | 480 | 7.90E-04 | 799 | 8.93E-4 |
| Terra | 34155 (Iridium 33 Debris) | 18 Dec 2015 | 18 Dec 2015 15:31 | 3682 | 1.47E-03 | 1020 | 8.08E-4 |
| OCO-2 | 38016 (Iridium 33 Debris) | 30 Dec 2015 | 24 Dec 2015 16:05 | 15531 | 8.59E-5 | 11680 | 6.69E-06 |

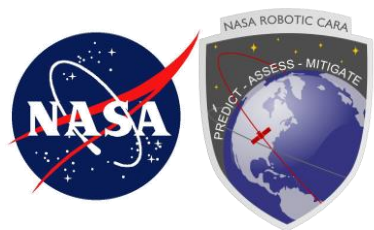
Updated as of JAN 2016



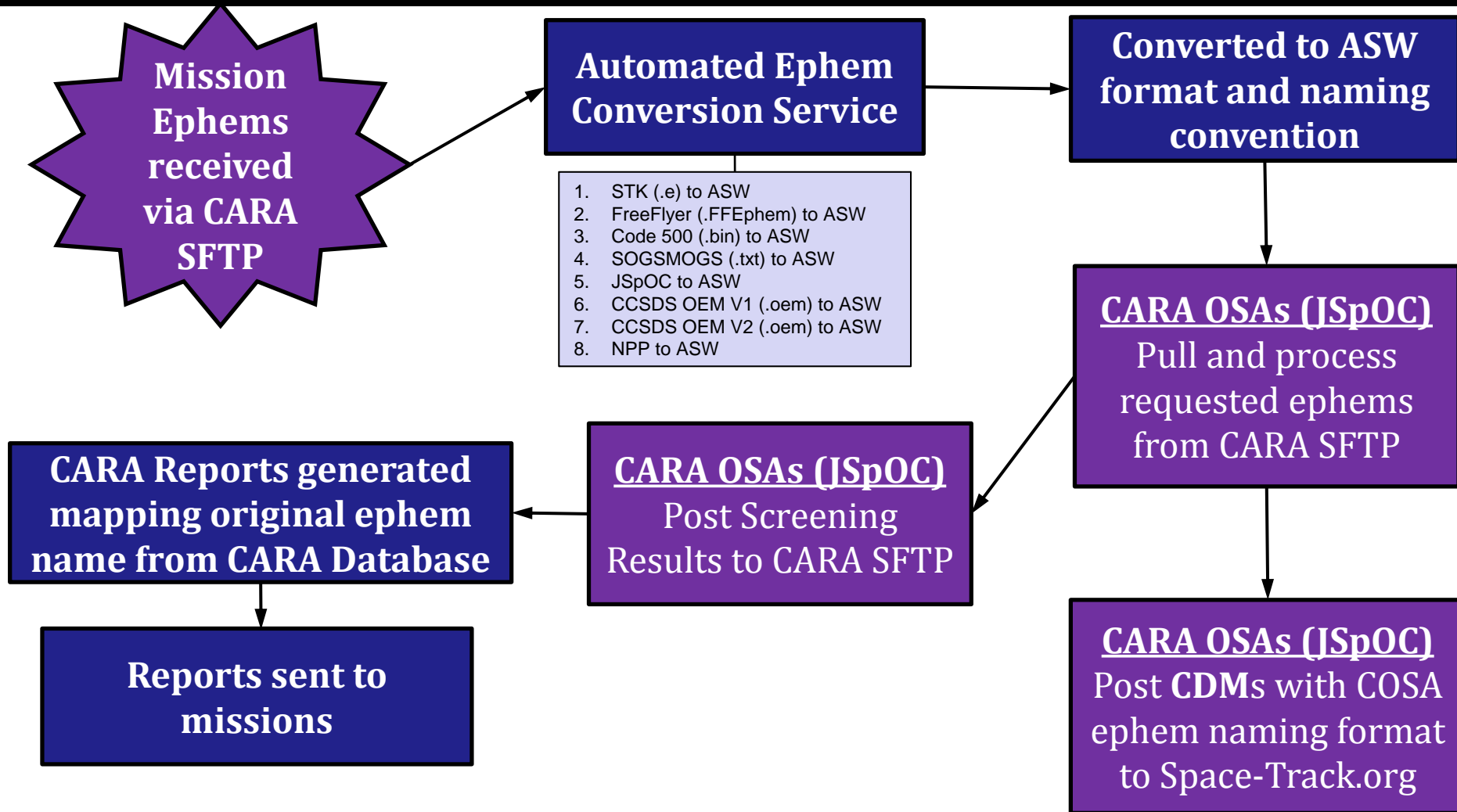
OPEN DISCUSSION

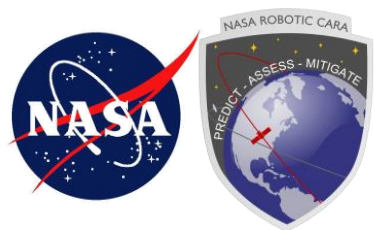


BACKUP



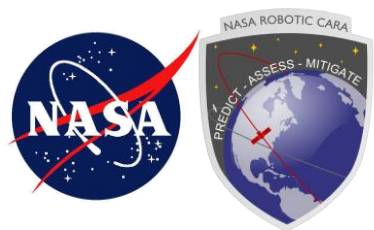
Ephemeris Naming Flow Through CARA Process





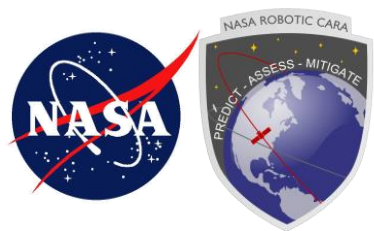
Risk Mitigation Maneuvers for 705-km Constellations

| Primary Object | Secondary Object | Maneuver Date | TCA (GMT) | Minimum Miss Distance Observed (m) | Maximum Pc Observed | Maximum F-value Observed |
|----------------|--------------------|---------------|------------------|------------------------------------|---------------------|--------------------------|
| Terra | SCOUT G-1 | 10/21/2005 | 10/23/2005 20:53 | 37 | 8.20E-02 | 9.97 |
| PARASOL | AnalystSat | 1/16/2007 | 1/17/2007 8:43 | 43 | 1.80E-02 | 8.91 |
| Terra | FengYun 1-C Debris | 6/22/2007 | 6/23/2007 21:44 | 18 | 1.60E-01 | 8.73 |
| CloudSat | SINAH 1 | 7/4/2007 | 7/6/2007 6:51 | 38 | 4.70E-02 | 9.22 |
| Aura | TRIAD 1 Debris | 6/26/2008 | 6/27/2008 15:34 | 11 | 4.80E-01 | 9.62 |
| CloudSat | Delta I Debris | 7/20/2008 | 7/21/2008 4:38 | 90 | 2.90E-03 | 8.48 |
| PARASOL | Fengyun 1-C Debris | 10/19/2008 | 10/20/2008 10:59 | 82 | 2.10E-02 | 6.42 |
| CloudSat | Cosmos 2251 | 4/23/2009 | 4/24/2009 13:29 | 52 | 4.80E-02 | 9.82 |
| EO-1 | SL-16 Debris | 5/11/2009 | 5/12/2009 16:59 | 43 | 1.60E-02 | 8.11 |
| PARASOL | Fengyun 1-C Debris | 9/29/2009 | 9/30/2009 10:54 | 9 | 1.20E-01 | 8.81 |
| Aqua | Fengyun 1-C Debris | 11/25/2009 | 11/26/2009 15:36 | 25 | 7.00E-02 | 9.23 |



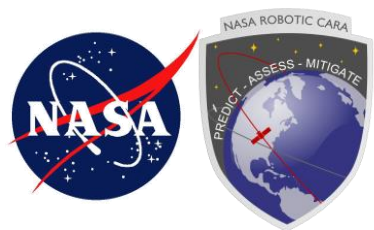
Risk Mitigation Maneuvers for 705-km Constellations cont.

| Primary Object | Secondary Object | Maneuver Date | TCA (GMT) | Minimum Miss Distance Observed (m) | Maximum Pc Observed | Maximum F-value Observed |
|----------------|-----------------------|-------------------|------------------|------------------------------------|---------------------|--------------------------|
| Landsat-7 | FORMOSAT 3D | 12/11/2009 | 12/16/2009 18:54 | 92 | 2.30E-02 | 9.07 |
| Terra | Iridium 33 Debris | 1/22/2010 | 1/23/2010 20:46 | 244 | 5.70E-03 | 8.15 |
| Landsat-5 | AnalystSat | 4/1/2010 | 4/1/2010 20:49 | 68 | 5.50E-03 | 7.6 |
| CloudSat | AnalystSat | 8/17/10 & 8/18/10 | 8/18/2010 5:25 | 34.9 | 1.17E-02 | 7.1 |
| Landsat-5 | Cosmos 2251 Debris | 8/24/2010 | 8/27/2010 12:58 | 55.8 | 5.15E-03 | 7.6 |
| CloudSat | SL-16 Debris | 10/11/2010 | 10/12/2010 4:15 | 230 | 3.80E-03 | 8.9 |
| CloudSat | Cosmos 2251 Debris | 10/13/2010 | 10/13/2010 23:58 | 1560 | 4.25E-03 | 6.2 |
| Aura | Cosmos 2251 Debris | 11/22/2010 | 11/24/2010 11:16 | 50 | 3.90E-02 | 9.5 |
| Aqua | Cosmos 2251 Debris | 1/2/2011 | 1/5/2011 18:17 | 94 | 8.40E-03 | 6.4 |
| Aqua | Iridium 33 Debris | 2/8/2011 | 2/8/2011 19:32 | 41 | 4.70E-02 | 8.6 |
| CALIPSO | OV2-1 | 2/18/2011 | 2/19/2011 20:47 | 95 | 2.20E-04 | 9 |
| Aqua | Thorad Agena D Debris | 3/1/2011 | 3/2/2011 2:45 | 204 | 3.41E-03 | 9 |



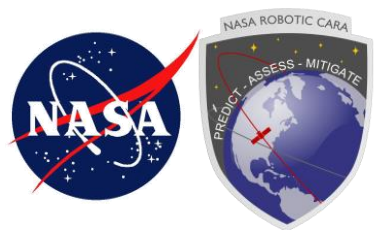
Risk Mitigation Maneuvers for 705-km Constellations cont.

| Primary Object | Secondary Object | Maneuver Date | TCA (GMT) | Minimum Miss Distance Observed (m) | Maximum Pc Observed | Maximum F-value Observed |
|----------------|-----------------------|---------------|------------------|------------------------------------|---------------------|--------------------------|
| CloudSat | Aqua | 6/18/2011 | 7/1/2011 0:13 | 280 | UNK | N/A |
| CloudSat | Terra | 10/6/2011 | 11/7/2011 0:33 | 1125 | UNK | UNK |
| Landsat-7 | Cosmos 374 Debris | 11/29/2011 | 11/30/2011 18:07 | 92 | 4.75E-03 | 7 |
| CloudSat | FengYun 1-C Debris | 12/14/2011 | 12/15/2011 18:59 | 220 | 1.79E-02 | UNK |
| Landsat-7 | FengYun 1-C Debris | 3/8/2012 | 3/9/2012 19:32 | 498 | 2.02E-03 | 9.1 |
| Landsat-7 | Meteor 1-10 Debris | 4/17/2012 | 4/18/2012 8:14 | 32 | 3.73E-02 | 7.8 |
| Aura | Cosmos 2251 Debris | 5/16/2012 | 5/17/2012 19:09 | 81 | 4.70E-04 | 8 |
| Landsat-5 | Thorad Agena D Debris | 6/29/2012 | 7/1/2012 1:46 | 34 | 5.42E-03 | 9 |
| CloudSat | SINAH 1 | 9/7/2012 | 9/8/2012 4:57 | 61 | 3.55E-03 | 9.2 |
| GCOM-W1 | Fengyun 1C Debris | 9/8/2012 | 9/8/2012 21:18 | 241 | 1.59E-03 | 7.3 |



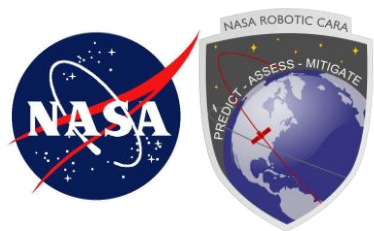
Risk Mitigation Maneuvers for 705-km Constellations cont.

| Primary Object | Secondary Object | Maneuver Date | TCA (GMT) | Minimum Miss Distance Observed (m) | Maximum Pc Observed | Maximum F-value Observed |
|----------------|----------------------|---------------|------------------|------------------------------------|---------------------|--------------------------|
| GCOM-W1 | SL-16 Debris | 9/25/2012 | 9/25/2012 20:54 | 125 | 4.68E-03 | 8.4 |
| CALIPSO | Cosmos 2251 Debris | 10/2/2012 | 10/2/2012 22:28 | 5 | 5.90E-02 | 9.6 |
| PARASOL | SL-16 Debris | 11/25/2012 | 11/25/2012 18:45 | 78 | 8.32E-03 | 8.6 |
| CALIPSO | Cosmos 2251 Debris | 1/5/2013 | 1/6/2013 13:51 | 94 | 2.43E-03 | 8.7 |
| Landsat-5 | AnalystSat | 2/12/2013 | 2/13/2013 12:29 | 58 | 5.86E-03 | 7.5 |
| Aqua | Thor Ablestar Debris | 3/10/2013 | 3/12/2013 4:02 | 74 | 2.57E-03 | 8.5 |
| CALIPSO | Iridium 33 Debris | 3/20/2013 | 3/20/2013 22:23 | 129 | 5.72E-03 | 9.3 |
| Aqua | Iridium 33 Debris | 3/23/2013 | 3/23/2013 11:17 | 329 | 3.92E-04 | 6.4 |
| Terra | Cosmos 1174 Debris | 3/24/2013 | 3/26/2013 4:24 | 113 | 2.38E-03 | 9.3 |
| CloudSat | Fengyun 1C Debris | 4/25/2013 | 4/26/2013 11:39 | 529 | 1.37e-03 | 6.8 |
| LDCM | NOAA 13 Debris | 5/5/2013 | 5/6/2013 19:53 | 248 | 1.96E-02 | 9.6 |
| Landsat-7 | CZ-4 Debris | 5/9/2013 | 5/10/2013 14:21 | 128 | 5.14E-04 | 8.9 |



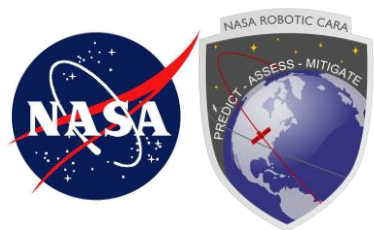
Risk Mitigation Maneuvers for 705-km Constellations cont.

| Primary Object | Secondary Object | Maneuver Date | TCA (GMT) | Minimum Miss Distance Observed (m) | Maximum Pc Observed | Maximum F-value Observed |
|----------------|-------------------|---------------|-------------------|------------------------------------|---------------------|--------------------------|
| GCOM-W1 | CZ-4 Debris | 10 May 2013 | 11 May 2013 22:24 | 69 | 6.81E-03 | 7.4 |
| GCOM-W1 | Fengyun 1C Debris | 23 Jun 2013 | 25 Jun 2013 13:00 | 162 | 5.58E-03 | 9.4 |
| Landsat 8 | AnalystSat | 15 Aug 2013 | 16 Aug 2013 11:39 | 1250 | 1.28E-03 | 6.4 |
| Terra | CZ-4 Debris | 18 Aug 2013 | 19 Aug 2013 07:43 | 79 | 6.72E-02 | 9.3 |
| Aura | SJ-11-02 | 02 Sep 2013 | 03 Sep 2013 07:02 | 320 | 2.23E-04 | 8.5 |
| GCOM-W1 | Fengyun 1C Debris | 19 Sep 2013 | 20 Sep 2013 05:55 | 184 | 1.69E-03 | 7.2 |
| CALIPSO | Cosmos 397 Debris | 24 Sep 2013 | 24 Sep 2013 18:31 | 115 | 2.42E-03 | 8.3 |
| Landsat 7 | SL-8 Debris | 01 Oct 2013 | 02 Oct 2013 20:53 | 58 | 7.51E-04 | 8.7 |
| Aqua | Iridium 33 Debris | 25 Oct 2013 | 25 Oct 2013 04:27 | 689 | 8.99E-04 | 8.8 |
| Terra | Fengyun 1C Debris | 17 Nov 2013 | 18 Nov 2013 05:42 | 272 | 1.01E-02 | 8.5 |



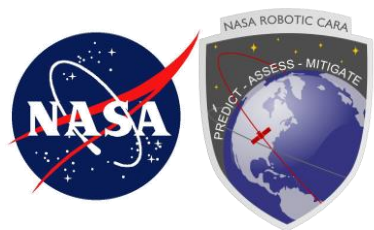
Risk Mitigation Maneuvers for 705-km Constellations cont.

| Primary Object | Secondary Object | Maneuver Date | TCA (GMT) | Minimum Miss Distance Observed (m) | Maximum Pc Observed | Maximum F-value Observed |
|----------------|---------------------|---------------|-------------------|------------------------------------|---------------------|--------------------------|
| Aqua | Cosmos 2251 Debris | 28 Nov 2013 | 28 Nov 2013 22:28 | 373 | 6.41E-04 | 8.1 |
| Terra | CZ-4 Debris | 10 Feb 2014 | 10 Feb 2014 11:52 | 152 | 1.24E-02 | 8.5 |
| Terra | Delta 1 Debris | 2014 Mar 21 | 23 Mar 2014 00:17 | 50 | 2.35E-03 | 8.6 |
| Landsat 7 | Delta 1 Debris | 2014 Apr 15 | 16 Apr 2014 17:10 | 362 | 8.63E-03 | 9.1 |
| GCOM-W1 | Iridium 33 Debris | 2014 Apr 22 | 22 Apr 2014 17:11 | 223 | 3.39E-03 | 8.0 |
| Landsat 7 | Cosmos 2251 Debris | 27 May 2014 | 28 May 2014 06:19 | 127 | 2.31E-02 | 8.4 |
| OCO-2 | AnalystSat | 24 Aug 2014 | 24 Aug 2014 01:47 | 147 | 8.84E-04 | 6.5 |
| Landsat 8 | Cosmost 2251 Debris | 28 Aug 2014 | 30 Aug 2014 19:15 | 384 | 3.02E-03 | 9.1 |
| Aura | Fengyun 1C Debris | 29 Aug 2014 | 02 Sep 2014 12:32 | 408 | 1.19E-03 | 6.7 |
| OCO-2 | CZ-4B Debris | 14 Sep 2014 | 14 Sep 2014 22:51 | 81 | 2.84E-04 | 7.8 |
| Landsat 7 | SL-8 Debris | 25 Sep 2014 | 25 Sep 2014 22:47 | 1447 | 4.16E-04 | 7.1 |



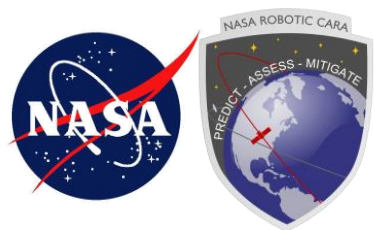
Risk Mitigation Maneuvers for 705-km Constellations cont.

| Primary Object | Secondary Object | Maneuver Date | TCA (GMT) | Minimum Miss Distance Observed (m) | Maximum Pc Observed |
|----------------|----------------------|---------------|-------------------|------------------------------------|---------------------|
| GCOM-W1 | SL-16 Debris | 12 Oct 2014 | 13 Oct 2014 08:03 | 1900 | 6.75E-04 |
| Aqua | Unknown | 21 Oct 2014 | 21 Oct 2014 04:17 | 4935 | 6.90E-04 |
| GCOM-W1 | Cosmos 1275 Debris | 09 Nov 2014 | 09 Nov 2014 23:44 | 69 | 3.91E-03 |
| Terra | Iridium 33 Debris | 31 Dec 2014 | 01 Jan 2015 06:24 | 206 | 9.67E-04 |
| OCO-2 | Cosmos 2251 Debris | 01 Jan 2015 | 02 Jan 2015 07:58 | 152 | 6.70E-04 |
| CloudSat | SL-8 Debris | 14 Mar 2015 | 15 Mar 2015 20:07 | 40 | 3.72E-04 |
| Landsat 8 | Cosmos 2251 Debris | 10 Apr 2015 | 10 Apr 2015 14:37 | 46 | 8.68E-04 |
| GCOM-W1 | DMSP 5D-2 F11 Debris | 13 Apr 2015 | 13 Apr 2015 06:06 | 1439 | 1.46E-03 |
| GCOM-W1 | SJ-11-01 | 20 May 2015 | 22 May 2015 14:27 | 455 | 2.27E-03 |
| Terra | Cosmos 2251 Debris | 27 May 2015 | 27 May 2015 23:13 | 57 | 1.86E-02 |



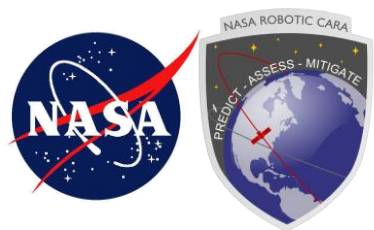
Re-planned, Postponed, Waived Off Maneuvers (705-km Constellations)

| Primary Object | Secondary Object | Maneuver Date | TCA (GMT) | Minimum Miss Distance Observed O/O (m) | Minimum Miss Distance Observed ASW (m) | Maximum Pc Observed |
|----------------|---------------------------|---------------|------------------|--|--|---------------------|
| Terra | Titan 3C Transtage Debris | UNK | 1/12/2006 17:46 | 88 | 334 | 0.00E+00 |
| Aura | Titan 3C Transtage Debris | 6/17/2008 | 6/13/2008 3:26 | 618 | 5671 | N/A |
| Aura | DMSP 5D-2 F11 debris | 6/17/2008 | 6/15/2008 20:34 | 628 | 7340 | N/A |
| Landsat-7 | Fengyun 1-C debris | 2/3/2009 | 1/14/2009 9:49 | 380 | 1055 | 5.13E-05 |
| CALIPSO | CZ-4 Debris | 11/23/2010 | 11/23/2010 3:12 | 1735 | 421 | 1.60E-03 |
| CloudSat | Monitor-E/SL-19 | 11/23/2010 | 11/23/2010 13:47 | 150 | 1377 | 0.00E+00 |
| Landsat-7 | AnalystSat | 12/21/2010 | 12/21/2010 19:43 | 673 | 441 | 2.35E-03 |
| Aqua | CloudSat | 6/8/2011 | 5/22/2011 0:00 | UNK | UNK | UNK |
| Aqua | Fengyun 1-C debris | 6/23/2011 | 6/23/2011 17:27 | 370 | 66 | 4.92E-02 |
| Aqua | COSMOS 2251 Debris | 8/25/2011 | 8/29/2011 3:57 | 195 | 30739 | 0.00E+00 |
| Aura | COSMOS 2251 Debris | 9/8/2011 | 9/3/2011 5:57 | 40 | 50 | 2.20E-03 |
| Landsat-7 | CZ-2C Debris | 10/6/2011 | 10/9/2011 1:16 | 87 | 3860 | 1.68E-06 |



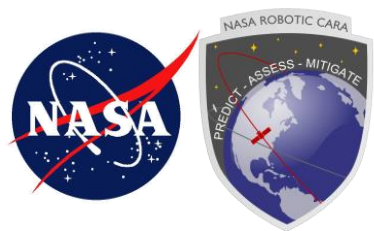
Re-planned, Postponed, Waived Off Maneuvers (705-km Constellations) cont.

| Primary Object | Secondary Object | Maneuver Date | TCA (GMT) | Minimum Miss Distance Observed O/O (m) | Minimum Miss Distance Observed ASW (m) | Maximum Pc Observed |
|----------------|---------------------------|---------------|------------------|--|--|---------------------|
| Aqua | CZ-4 Debris | 10/25/2011 | 10/26/2011 11:13 | 12 | 1349 | 1.80E-03 |
| Aqua | Titan 3C Transtage Debris | 12/20/2011 | 12/16/2011 19:36 | 388 | 45775 | 0.00E+00 |
| Terra | Nigeriasat-2 | 5/31/2012 | 6/1/2012 22:49 | 190 | 19970 | 0.00E+00 |
| Landsat-7 | Fengyun 1-C Debris | 6/19/2012 | 6/21/2012 13:40 | 415 | 641 | 1.01E-04 |
| GCOM-W1 | Iridium 33 Debris | 6/28/2012 | 6/29/2012 6:23 | 3487 | 4397 | N/A |
| Aura | AnalystSat | 8/29/2012 | 9/2/2012 13:28 | 230 | 63 | 2.74E-03 |
| Landsat-5 | COSMOS 2251 Debris | 9/13/2012 | 9/11/2012 17:47 | 103 | 97 | 4.83E-03 |
| Aqua | AnalystSat | 9/13/2012 | 9/16/2012 18:50 | 63005 | 345 | 0.00E+00 |
| Aqua | COSMOS 2251 Debris | 1/25/2013 | 1/28/2013 19:46 | 235 | 190 | 3.23E-04 |
| Aura | Latinsat B | 4/3/2013 | 3/24/2013 22:04 | 793 | 5096 | 7.28E-16 |
| Aura | SL-16 Debris | 4/3/2013 | 3/30/2013 3:08 | 80 | 20095 | 3.24E-103 |
| LDCM | Atlas Centaur R/B | 4/3/2013 | 4/4/2013 4:11 | 227 | 5707 | 1.88E-52 |



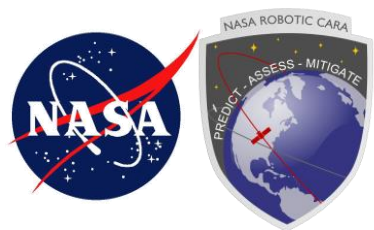
Re-planned, Postponed, Waived Off Maneuvers (705-km Constellations) cont.

| Primary Object | Secondary Object | Maneuver Date | TCA (GMT) | Minimum Miss Distance Observed O/O (m) | Minimum Miss Distance Observed ASW (m) | Maximum Pc Observed |
|----------------|----------------------|---------------|-------------------|--|--|---------------------|
| Aqua | PSLV Debris | 30 Apr 2013 | 24 Apr 2013 07:44 | 238 | 3810 | 6.63E-08 |
| Landsat 8 | SL-8 Debris | 21 Jul 2013 | 23 Jul 2013 19:56 | 1549 | 266 | 1.26E-03 |
| Landsat 8 | NOAA 13 Debris | 26 Sep 2013 | 28 Sep 2013 03:16 | 271 | 209 | 1.44E-08 |
| Aura | Cosmos 2251 Debris | 15 Nov 2013 | 18 Nov 2013 17:50 | 157 | 3822 | 1.27E-02 |
| Aqua | SL-16 Debris | 14 Jan 2014 | 09 Jan 2014 23:30 | 1402 | 3355 | 2.50E-05 |
| Aqua | Cosmos 2251 Debris | 14 Jan 2014 | 14 Jan 2014 17:24 | 7979 | 2930 | 4.06E-06 |
| Terra | Magion 2 | 26 Feb 2014 | 26 Feb 2014 02:42 | 280 | 6806 | 1.14E-06 |
| GCOM-W1 | CZ-2D Debris | 02 Apr 2014 | 27 Mar 2014 16:06 | 1454 | 11725 | 1.82E-04 |
| CloudSat | AnalystSat | 04 Apr 2014 | 03 Apr 2014 22:42 | 211 | 10269 | 1.30E-04 |
| CloudSat | Thor Ablestar Debris | 21 May 2014 | 22 May 2014 12:02 | 152 | 1199 | 9.00E-06 |
| Aura | Cosmos 2251 Debris | 19 Jun 2014 | 20 Jun 2014 05:22 | 137 | 64 | 8.80E-05 |
| Landsat 8 | Cosmos 2251 Debris | 24 Sep 2014 | 24 Sep 2014 01:52 | 154 | 2628 | 0.00E+00 |



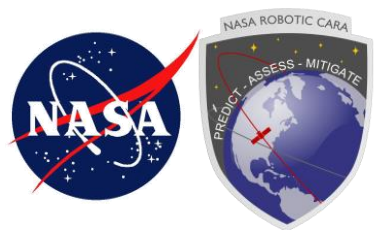
Re-planned, Postponed, Waived Off Maneuvers (705-km Constellations) cont.

| Primary Object | Secondary Object | Maneuver Date | TCA (GMT) | Minimum Miss Distance Observed O/O (m) | Minimum Miss Distance Observed ASW (m) | Maximum Pc Observed |
|----------------|--------------------|---------------|-------------------|--|--|---------------------|
| Terra | Cosmos 2251 Debris | 13 Nov 2014 | 08 Nov 2014 22:46 | 133 | 6067 | 0.00E+00 |
| Calipso | CZ-2C Debris | 05 Dec 2014 | 06 Dec 2014 06:49 | 1409 | N/A | N/A |
| Terra | Iridium 33 Debris | 12 Dec 2014 | 13 Dec 2014 15:44 | 4110 | 4320 | 2.13E-04 |
| Aura | Fengyun 1-C debris | 28 Jan 2015 | 24 Jan 2015 13:34 | 1292 | 1460 | 6.82E-04 |
| Aura | CZ-2C Debris | 28 Feb 2015 | 07 Feb 2015 02:16 | 298 | 153 | 1.04E-03 |
| Aura | CBERS 1 Debris | 28 Feb 2015 | 18 Feb 2015 22:36 | 150 | 607 | 6.06E-09 |
| Aqua | Cosmos 2251 Debris | 22 May 2015 | 22 May 2015 23:47 | 149 | 395 | 1.24E-04 |



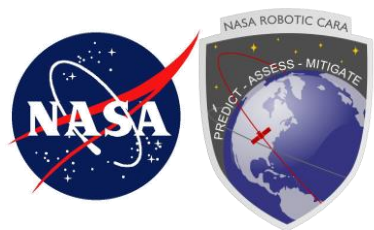
Normalizing HIE Trend Data

| Year | No. of Missions | Notes |
|------|-----------------|---|
| 2005 | 9 | L5, L7, Terra, Aqua, Aura, EO-1, Parasol, SAC-C, IceSAT |
| 2006 | 10.5 | Added CALIPSO and PARASOL in April; 0.75 yrs each |
| 2007 | 11 | |
| 2008 | 11 | |
| 2009 | 11 | |
| 2010 | 10.6 | Stopped supporting IceSAT in August |
| 2011 | 10 | |
| 2012 | 10.5 | Added GCOM-W1 in May |
| 2013 | 11 | Added L8 in February; dropped Landsat 5 in June |
| 2014 | 10.5 | Added OCO-2 in July; dropped SAC-C, PARASOL |
| 2015 | 10 | |
| 2016 | 10 | |



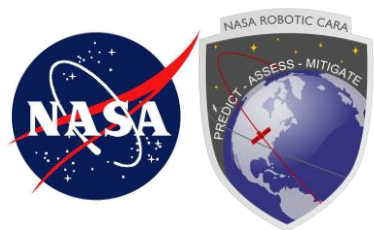
MTS 2.1 – Use Cases [1 of 2]

| Primary | | Secondary | Case Description |
|------------------------------|------------|------------------|---|
| <i>State</i> | <i>Cov</i> | <i>State/Cov</i> | |
| OCM | OCM | OCM/OCM | Maneuver Planning |
| OCM | VCM | OCM/OCM | Maneuver Planning |
| VCM | OCM | OCM/OCM | Maneuver Planning |
| VCM | VCM | OCM/OCM | Maneuver Planning |
| EPH with ASW conjunction set | OCM | ASW OCM/OCM | Burn sensitivity pre-ephem screening with ASW OCM set, but O/O ephem with burn included [Using primary covariance from the OCM] |
| EPH with O/O conjunction set | OCM | O/O OCM/OCM | Nominal burn sensitivity post-ephem screening with O/O OCM set [Using primary covariance from the OCM] |



MTS 2.1 – Use Cases [2 of 2]

| Primary | | Secondary | Case Description |
|------------------------------|------------|------------------|---|
| <i>State</i> | <i>Cov</i> | <i>State/Cov</i> | |
| EPH with O/O conjunction set | VCM | O/O OCM/OCM | Burn sensitivity post-ephem screening with O/O OCM set [Using primary covariance from the VCM] |
| EPH with ASW conjunction set | EPH | ASW OCM/OCM | Burn sensitivity pre-ephem screening with ASW OCM set, but O/O ephem with burn included [Using primary covariance from the VCM] |
| EPH | EPH | OCM/OCM | Nominal burn sensitivity post-ephem screening with O/O OCM set [Using primary covariance from ephem] |
| EPH | SYN | OCM/OCM | Nominal burn sensitivity post-ephem screening with O/O OCM set [Using primary covariance from the synthesized covariance table] |



Sensor Coverage Tool: Disclaimer

Sensor Coverage information is provided with several caveats that must be considered when evaluating the data for conjunction and risk analysis. The provided theoretical probability of detection (P_d) uses view geometry and expected signal to noise to represent tracking opportunities that are physically possible. Theoretical P_d does not correlate well to actual tracks received. The provided empirical P_d is based off of the recent historical tasking response data for a sensor and provides the set of tracking opportunities that have a reasonable potential to translate into actual tracks. Due to a variety of factors (sensor, tracking, resource limitations, etc.), there is the possibility that tracking opportunities with reasonable empirical P_d 's will not translate into actual tracks.

CARA provides this information to give insight into when the conjunction data has the potential to change. CARA will use this in support of mission decision points. At the CARA analyst's discretion, CARA will inquire about whether tracking opportunities near decision points have translated into actual tracks and request updates as appropriate. CARA will not inquire about tracking after every tracking opportunity. Missions should provide realistic decision points at which they expect to use this information.